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Patent Application

Title: Power Amplifier with Multiple Power Supplies

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TITLE: Power Amplifier with Multiple Power Supplies

Field of the Invention

[01] This invention relates to power amplifiers. More particularly, the invention relates to power amplifiers which efficiently amplify one or more input signals with a large dynamic range while producing low electromagnetic emissions.

Background of the Invention

[02] A music audio signal or a movie soundtrack typically has a large dynamic range. Such signals often have a peak-to-average magnitude ratio of 8-to-1 or even higher. In addition, peaks in such signals are relatively infrequent and at most times, the signal has a magnitude close to its average magnitude. A power amplifier for such a signal must be capable of producing an output signal with corresponding high peaks and with a comparatively low average magnitude. A number of power amplifiers are known which vary the power supplied to the power amplifier's main amplification circuit (or amplifier) so that there is limited headroom between the supplied power and the magnitude of the power amplifier's output signal.

[03] For example, U.S. patent 3,772,606 describes a linear class H power amplifier with four fixed power rails. Two of the rails are used to supply power to the amplifier of the power amplifier during positive half waves of the output signal and the other two rails are used to supply power to the power amplifier during negative half waves of the output signal. Of the two rails used to supply the main amplifier during the positive half waves of the output signal, one is a low voltage rail and the other is a high voltage rail. Only the low voltage rail is used to power the amplifier when the output signal has a magnitude well below that of the low voltage rail. As the output signal approaches the low voltage rail, the high voltage rail is turned on to supply additional power. This device effectively reduces the average voltage drop (i.e. the headroom) from the supply rail to the output signal, thereby improving the efficiency of the power amplifier. However, this solution is far from ideal, especially where the output signal has an average level substantially less than the lower supply rail, or

slightly higher than the lower supply rail. In either case, there will still be substantial headroom between the output signal and the power supplied to the amplifier.

[04] U.S. patent 4,430,625 describes a power amplifier that addresses this problem by providing low voltage rails which have a variable magnitude proportional to the magnitude of the output signal. The low voltage rails are provided by a switching regulator and their magnitude is controlled using a fixed frequency pulse width modulated (PWM) control signal. When the low voltage rails are insufficient to power the amplifier, high voltage rails provided by fast acting linear regulators are utilized to make up for the deficiency. This device further reduces the headroom between the output signal and the power supply to the amplifier when the output signal is lower than the low voltage rails. However, it is susceptible to high electromagnetic interference (EMI) emissions due to its hard-switching low voltage regulators. In addition, this device has no mechanism for predicting the power required by the amplifier to generate the output signal at any particular time. This results in the power supply from the switching regulators being deficient when the input signal rises rapidly and in the worst case may cause the switching regulators to be deficient during every half wave (or during many half waves) of the output signal. This in turn leads to overuse of the linear regulators, increasing the power consumption of the power amplifier and decreasing its overall efficiency.

[05] U.S. patent 5,347,230 describes a power amplifier which attempts to reduce the usage of the linear regulators by monitoring the current in the linear regulator and controlling the output of the switching regulator in a way that minimizes the current drawn from the linear regulator. The control circuit of this power amplifier is responsive to changes in the output signal to vary the power provided by the switching regulators. This design, which is responsive rather than predictive, leads to a slow response time for the switching regulators, possibly resulting in increased usage of the linear regulators. Furthermore, this device utilizes fast-switching switching regulators which generate large EMI emissions. In addition, this device suffers from a load dumping problem which may force a high current from a current source through a high impedance load, resulting in a large voltage spike across the load.

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[06] None of these devices is well suited for use with multiple channels. Most modern audio amplifiers produce at least five output channels (i.e. surround sound systems) and many produce six or more output channels (including a sub-woofer output). This is in contrast to the two channel systems (i.e. left and right signals) which were common in the past. Providing five or more duplicate power supply circuits for each power amplifier within a single audio amplifier increases both the size and cost of the audio amplifier.

[07] Furthermore, none of these devices provide for protection of the amplification from over-current, over-temperature or other overload conditions. Such protection is essential for practical commercial use of a power amplifier circuit.

[08] Accordingly, there is a need for a power amplifier for audio signals that provides an efficient power supply with low EMI emissions and with low headroom between the power supplied to the amplification circuit and the output signal of the power amplifier. It is preferable if the power amplifier has a predictive control system that allows the headroom to be reduced while ensuring that sufficient power is provided to the amplification circuit (or circuits) at all times. It is also preferable that the control circuit and regulation system of the power amplifier be adaptable for use with multiple channels. It is also desirable that the power amplifier be adaptable to protect the amplification circuit of each channel so as to prevent the amplification circuit from being damaged by over-current, over-temperature or other overload conditions.

Summary of the Invention

[09] In a first embodiment, present invention provides: a power amplifier for receiving an input signal at an input terminal and producing an output signal at an output terminal, said output signal corresponding to said input terminal, said power amplifier having a first power supply circuit comprising: an amplifier coupled to said input terminal for receiving said input signal and coupled to said output terminal for providing said output signal, said amplifier having a power input terminal for receiving a power input signal; a switching regulator coupled to said power input terminal for providing a switching power signal to said amplifier, wherein

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said switching power signal forms a first part of power input signal; a linear regulator coupled to said power input terminal, said linear regulator being selectively engageable to provide a linear power signal to said amplifier, wherein said linear power signal forms a second part of said power input signal; an input signal processing circuit coupled to said input terminal for receiving said input signal and for providing a rectified signal indicating the amount of power required by said amplifier; a control circuit coupled to said input signal processing circuit and to said power input terminal for controlling said switching power signal and said linear power signal in response to an error signal corresponding to a between said rectified signal and said power input signal; a linear regulator control circuit coupled to said input signal processing circuit for receiving said rectified signal and coupled to said linear regulator for controlling the engagement of said linear regulator in response to said rectified signal.

[10] In a second embodiment, the present invention provides a power amplifier for receiving an input signal at an input terminal and producing an output signal at an output terminal, said output signal corresponding to said input terminal, said power amplifier having a first power supply circuit comprising: an EMI isolation circuit coupled to said input terminal for receiving said input signal and to an internal input node for providing an EMI-decoupled signal corresponding to said input signal; an amplifier coupled to said input terminal for receiving said input signal and coupled to said output terminal for providing said output signal, said amplifier having a power input terminal for receiving a power input signal; a switching regulator coupled to said power input terminal for providing a switching power signal to said amplifier, wherein said switching power signal forms a first part of power input signal; a linear regulator coupled to said power input terminal, said linear regulator being selectively engageable to provide a linear power signal to said amplifier, wherein said linear power signal forms a second part of said power input signal; an input signal processing circuit coupled to said internal input node for receiving said EMI-decoupled signal and for providing a rectified signal indicating the amount of power required by said amplifier; a control circuit coupled to said internal input signal processing circuit and to said power input terminal for controlling said switching

power signal and said linear power signal in response to an error signal corresponding to a between said rectified signal and said power input signal; a linear regulator control circuit coupled to said input signal processing circuit for receiving said rectified signal and coupled to said linear regulator for controlling the
5 engagement of said linear regulator in response to said rectified signal.

Brief Description of the Drawings

[11] The present invention will be described, by way of example only, with reference to the drawings, in which:

[12] Figure 1 is a block diagram of a first embodiment of a power amplifier
10 according to the present invention;

Figure 2 illustrates a second embodiment of a power amplifier according to the present invention;

Figure 3 illustrates a third embodiment of a power amplifier according to the present invention;

Figure 4 illustrates a fourth embodiment of a power amplifier according to the present invention;

Figure 5 illustrates a illustrates the headroom between a power supply signal of the power amplifier of Figure 4 and a pair of input signals to that power amplifier;

Figure 6 illustrates a fifth embodiment of a power amplifier according to the present invention;

Figure 7 illustrates the relationship between power signal produced by a switching regulator and a low voltage power supply of the power amplifier of Figure 6;

Figure 8 illustrates a sixth embodiment of a power amplifier according to
25 the present invention;

Figure 9 illustrates a pulse of a power signal produced by a resonant switching regulator of the power amplifier of Figure 8;

Figure 10 illustrates a seventh embodiment of a power amplifier according to the present invention;

Figure 11 illustrates part of the feedback control circuit of the power amplifier of Figure 10;

Figure 12 illustrates another part of the feedback control circuit of the power amplifier of Figure 10;

Figure 13 is a timing diagram illustrating the production of PDM control signal of the power amplifier of Figure 10;

Figure 14 illustrates an eighth embodiment of a power amplifier according to the present invention;

Figure 15 illustrates an input filtration circuit according to the present invention which may be used with a power amplifier;

Figure 16 is a block diagram of a ninth embodiment of a power amplifier according to the present invention;

Figure 17 illustrates a tenth embodiment of a power amplifier according to the present invention; and

Figure 18 is a timing diagram illustrating the operation of the power amplifier of Figure 17.

Detailed Description of Exemplary Embodiments

[13] Several exemplary power amplifiers made according to the present invention will now be described. Corresponding components of each power amplifier are identified by the same or similar reference numerals.

[14] Reference is first made to Figure 1, which is a block diagram of a power amplifier 100 according to the present invention. Power amplifier 100 has an input terminal 102, a positive half circuit 108, an amplifier 104, and output terminal 106 and a negative half circuit 110.

[15] Input terminal 102 is configured to receive an input signal 130. Amplifier 104 is coupled to input terminal 102 to receive input signal 130 and to provide a corresponding output signal 132 at an output terminal 106. A load 134 is coupled to output terminal 106 to receive output signal 132.

[16] Positive half circuit 108 has an input signal compensation block 105, a summer 137, a control circuit 116, a main power supply 118, a transient detect block

119, a transient power supply 123 and an output power signal compensation block 135. Negative half circuit 110 has the same structure as positive half circuit 108 and has a complementary operation. Only positive half circuit 108 will be described in detail.

5 **[17]** Input compensation block 105 is coupled to input terminal 102 to receive input signal 130 and to provide a compensated input signal 140 at a terminal 117. Amplifier 104 receives a power signal V_t from a positive power terminal 136. Power signal V_t is the sum of a power signal V_s provided by main power supply 118 and a power signal V_l provided by transient power supply 123. The voltage of power signal
10 V_t is equal to the greater of the voltages of power signals V_s and V_l . Output power signal compensation block 135 is coupled to positive power terminal 136 and provides a compensated power signal V_{tr} , which has a range comparable to that of compensated input signal 140. Summer 137 compares compensated input signal 140 to compensated power signal V_{tr} and provides an error signal 139. Input compensation block 105 and output power signal compensation block 135 are configured to produce

[18] Control circuit 116 receives error signal 139 and produces a first control signal 142 to control main power supply 118. Main power supply 118 is responsive to first control signal 142 and produces power signal V_s with a magnitude corresponding to control signal 142.

[19] At any particular time when power amplifier 100 is in operation, amplifier 104 will require sufficient power V_{req} to produce output power signal 132. The specific amount of power V_{req} required will vary depending on the magnitude of input signal 130, the amount of amplification desired and power required to power the
25 components of amplifier 104. Any excess power supplied to amplifier 104 will be dissipated in amplifier 104. Such dissipated power is lost and increases the power consumption of power amplifier 100. Accordingly, it is desirable to reduce the headroom between power signal V_t and the required power level V_{req} . For reasons explained below, it is desirable to provide a safety margin between V_t and V_{req} .

30 **[20]** Input compensation block 105 and output power signal compensation block 135 are configured to produce compensated input signal 140 and

compensated power signal V_{tr} such that error signal 139 will be zero or almost zero (i.e. compensated input signal 140 will be approximately equal to compensated power signal V_{tr}) when output power signal V_t has a magnitude V_{targ} that is slightly greater than V_{req} . Control circuit 116 produces control signal 142 so that main power supply 118 produces power signal V_s with a magnitude equal to V_{targ} . This condition is the "normal operation" of power amplifier 100. Under normal operation, transient power supply 123 is inoperative.

[21] Power signal V_s thus follows the waveform of output signal 132 with a headroom of $V_{targ} - V_{req}$, during the normal operation of power amplifier 100. For various reasons (described below), it may be desirable to reduce the slewing rate of main power supply 118. This can have the result that, if a large transient occurs in the input signal 130, power signal V_s will not be able to track output signal 132. Power signal V_s may have a magnitude less than V_{targ} or even less than V_{req} for a finite time.

[22] During this finite time, power amplifier 100 enters a "transient operation" and transient power supply 123 is engaged to provide power signal V_t to amplifier 104. Transient detection block 119 monitors compensated input power signal 140 at terminal 117 and, when a transient that exceeds a selected threshold occurs in input signal 130, transient detection block 119 enables transient power supply 123. The threshold is selected so that transient power supply 123 will be engaged when main power supply 118 is unlikely to be able to provide power signal V_s with a magnitude approximately equal to V_{targ} . The selection of the threshold will depend on the slew rate of main power supply 118.

[23] Transient power supply 123 has a very short slewing time and produces power signal V_t in response to a second control signal 144 provided by control circuit 116. Control circuit 116 configures control signal 144 so that power signal V_t will be approximately equal to V_{targ} . (The magnitude of power signal V_t is discussed in detail below.) When transient detection block 119 enables transient power supply 123, transient power supply 123 quickly produces power signal V_t approximately equal to V_{targ} . Power signal V_t thereby has a magnitude approximately equal to V_{targ} , providing approximately the desired amount of headroom for amplifier 104.

[24] Reference is next made to Figure 2, which is a block diagram of a second power amplifier 200 made according to the present invention. Power amplifier 200 has an input terminal 202, an amplifier 204, an output terminal 206, a positive half circuit 208 and a negative half circuit 210.

[25] Input terminal 202 is configured to receive an input signal 230. Amplifier 204 is coupled to input terminal 202 to receive input signal 230 and to provide an amplified output signal 232 corresponding to input signal 230 at output terminal 206. A load 234 is coupled to output terminal 206 to receive output signal 232. Amplifier 204 receives power from a positive power input terminal 236.

[26] Only the positive half circuit 208 of power amplifier 200 will be described in detail here. Positive half circuit 208 is operative to power amplifier 204 during positive half waves of output signal 232. Negative half circuit 210 has the same construction as positive half circuit 208 and has a complementary operation, providing power to amplifier 204 during negative half waves of output signal 232.

[27] Positive half circuit 208 includes an input signal compensation block 205, a transient detect block 219, a control circuit 216, a power source 212, a main power supply 218, a transient power supply 223, a summer 237, and an output power signal compensation block 235. Input signal compensation block 105 includes an offset block 211, frequency compensation block 214 and a rectifier 215. Transient detect block includes a peak detector 220, a differentiator 222 and a comparator 255. Main power supply 218 is a switching regulator. Transient power supply 223 includes a switch 224 and a linear regulator 226. Output power signal compensation block 235 comprises an amplifier.

[28] Offset block 211 is coupled to input terminal 202 to receive input signal 230. Offset block 211 adds a relatively small selected offset to input signal 230 to provide an offset input signal 231. Typically, the offset added by offset block 211 will be less than 10% of the expected 0-to-peak range of input signal 230 and is selected to ensure that the power provided to amplifier 204 by positive half circuit 208 is slightly higher than is actually required by amplifier 204 to generate output signal 232 (i.e. to ensure that V_{targ} is slightly higher than V_{req}).

[29] Frequency compensation block 214 is coupled to offset block 211 to receive offset input signal 231. Frequency compensation block 214 provides a frequency compensated signal 238 corresponding to offset input signal 231 to rectifier 215. Frequency compensation block 214 may be implemented as a phase lead network to (i) increase the amplitude of frequency compensated signal 238 at higher frequencies and to (ii) phase advance the voltage of frequency compensated signal 238 with respect to its current, as compared to the phase angle of input signal 230.

[30] Rectifier 215 receives frequency compensated signal 238 and provides a corresponding half wave rectified signal 240 at terminal 217. Rectifier 215 is a half wave rectifier which essentially discards negative portions of frequency compensated signal 238. The negative portions frequency compensated signal 238 are not required in positive half circuit 208 since positive half circuit 208 provides power to amplifier 204 only during positive half waves of output signal 232.

[31] Rectified signal 240, which is analogous to the compensated input signal 140 of power amplifier 100 (Figure 1), corresponds to the magnitude of offset input signal 231, and therefore corresponds generally to the magnitude of output signal 232 and to the power required by amplifier 240 to generate output signal 232 during a positive half wave of input signal 230. The offset added to offset input signal 231 by offset block 211 results in rectified signal 240 reflecting a slightly higher power level than is actually required by amplifier 204.

[32] Amplifier 204 receives a power signal V_t from a positive amplifier power terminal 236. Power signal V_t is the sum of a power signal V_s provided by main power supply 218 and a power signal V_i provided by transient power supply 223. Output power signal compensation block 235 is coupled to terminal 236 to receive power signal V_t and provide a reduced power signal V_{tr} , which has a range comparable to rectified signal 240. Reduced power signal V_{tr} has the same magnitude as rectified signal 240 when power signal V_t is providing sufficient power for amplifier 204 to generate the required output signal 232 with approximately the headroom configured by offset block 211.

[33] Summer 237 receives rectified signal 240 and subtracts reduced power signal V_{tr} to provide an error signal 239. At any point in time, error signal 239 represents the difference between the power required by amplifier 204 to produce output signal 232 (i.e. as represented by rectified signal 240) and the power presently being supplied to amplifier 204 (i.e. power signal V_t).

[34] Control circuit 216 is coupled to summer 237 to receive error signal 239. Control circuit 216 provides a first control signal 242 at a first control terminal 241 and a second control signal 244 at a second control terminal 243 in response to error signal 239. In power amplifier 200, control signal 242 is a pulse width modulated (PWM) control signal.

[35] Main power supply 218 is coupled to power source 212 to receive electrical power. Power source 212 has an output voltage of V_{max} . Main power supply 218 is a switching regulator and includes a switch 246 and a diode 248. Switch 246 is coupled to control terminal 241 and is responsive to PWM control signal 242 to produce a power signal V_{si} . Diode 248 ensures that current may flow in main power supply 218 at all times (i.e. when switch 246 is open, current may flow from ground through diode 248). Main power supply 218 also includes an integrating LC filter 250, which smooths power signal V_{si} to produce power signal V_s , which is delivered to positive power terminal 236 through diode 251.

[36] Amplifier 204 receives power signal V_s from positive power terminal 236. Amplifier 204 requires sufficient power V_{req} to produce output signal 232 and to power the components of amplifier 204 itself. Due to the small offset added by offset block 211, error signal 239 indicates that a slightly larger power signal is required by amplifier 204 than the power V_{req} that is actually required. As a result, control circuit 216 sets control signal 242 such that main power supply 218 will produce a power signal V_{targ} , which is slightly higher than the power V_{req} required by amplifier 204. Amplifier 204 will therefore ideally have a headroom equal to $V_{targ} - V_{req}$.

[37] Due to the phase lead effect of frequency compensation block 214, rectified signal 240 and control signal 242 will be advanced compared to the time at which amplifier 204 will actually receive the corresponding part (i.e. the current) of input signal 230. As a result, main power supply 218 will begin to shift its output

power signal V_s to the power level V_{req} required by amplifier 204 before amplifier 204 actually requires that level of power. In this way, the phase lead effect of frequency compensation block 214 gives main power supply 218 more time to respond to changes in the power level required by amplifier 204 to produce output signal 232. A similar predictive effect could be achieved by removing frequency compensation block 238 and differentiating rectified signal 240 with respect to time before it is fed to summer 239. This approach would result in a change in the waveform of the output power signal V_s of main power supply 218 since rectified signal 240 is not a sinusoidal signal.

[38] The small excess power (i.e. the headroom) in power signal V_s ($V_{targ} - V_{req}$) is dissipated in amplifier 204. Ideally, the excess power in power signal V_s would be zero or almost zero, although such an ideal result cannot practically be achieved. One reason for this is that power signal V_s will exhibit some degree of ripple. Power signal V_{si} is produced by the operation of switch 246 and will accordingly have a fairly high degree of ripple and may actually have substantial high frequency components. Filter 250 operates to integrate power signal V_{si} and smooth it thereby producing power signal V_s . However, power signal V_s will still exhibit some ripple, and it is necessary to ensure that even when the ripple causes power signal V_s to be below V_{targ} , it is still sufficient to power amplifier 204. For example, if output signal 232 has a magnitude of 10 volts at a particular point in time and exhibits a symmetrical ripple of 5 volts, then V_{targ} must be set to at least 12.5 volts so that even when power signal V_s is at it lowest level (during that particular time), which will be 12.5-2.5 volts, it will provide sufficient power to amplifier 204. More practically, in this example, V_{targ} may be set to 13.5 volts or more to provide an additional safety margin, to accommodate for the voltage drop across diode 251 and to provide power for the components of amplifier 204.

[39] The combination of the effect of offset block 211 and the phase lead effect of frequency compensation block 214 is to configure main power supply 218 to produce a power signal V_s which has a slightly higher magnitude than is required by amplifier 204, and which is generally matched in time to the power needs of amplifier 204. A person skilled in the art will be capable of adjusting the offset added by offset

block 211 and the magnitude of the phase lead effect of frequency compensation block 214 to provide an appropriate power signal V_s .

[40] When the frequency of input signal 230 is relatively low, power signal V_s will follow the waveform of output signal 232, with some headroom. As the slew rate of input signal 230 rises, main power supply 218 may be unable to change the magnitude of power signal V_s sufficiently quickly to follow output signal 232, which will have a correspondingly high slew rate. (Main power supply 218, which is a switching power regulator, has an intentionally limited slew rate, which is discussed below, increasing the possibility that this will occur.) When this occurs, power signal V_s will follow the envelope of output signal 232. However, due to the slow slew rate of main power supply 218 and the high slew rate of the output signal 232, output signal V_s may not have any headroom between it and the envelope of output signal 232. In fact, output signal V_s may be able to follow only the average of the envelope of output signal 232 and may actually be lower than output signal 232 at times, and may therefore be insufficient to power amplifier 204.

[41] As mentioned above, frequency compensation block 214 increases the amplitude of frequency compensated signal 238 at higher frequencies. As a result, when higher frequencies are present in input signal, rectified signal 240 will be magnified in comparison to input signal 230, and therefore, control circuit 216 will regulate main power supply 218 to a higher target power level V_{targ} . If the increased amplitude of frequency compensated signal 238 at high frequencies is sufficient, then main power supply 218 may provide a sufficient power signal V_s to power amplifier 204.

[42] Another mechanism for ensuring that main power supply 218 produces a power signal V_s that is sufficient to power amplifier 204 may be incorporated into offset block 211. In power amplifier 200, offset block 211 adds a fixed offset to input signal 230 to produce offset fixed signal 231. In an alternative embodiment of a power amplifier according to the present invention, offset block 211 may be configured to detect the frequency components on input signal 230 and to add a smaller offset to input signal 230 if the highest frequency component is lower than a selected frequency and to add a larger offset to input signal 230 if frequency components

exceeding equal to or exceeding the selected frequency exist. This will result in a larger power signal V_s when input signal 230 has frequency components higher than the selected frequency, thereby providing a higher headroom between the required power level V_{req} and the target power level V_{targ} .

5 [43] One skilled in the art will recognize that in power amplifier 200, the addition of a fixed offset to input signal 230 will cause a part of each negative half wave of input signal 230 (immediately before the beginning and after the end of each positive half wave) to have a magnitude greater than 0, which then results in that part of each negative half wave being treated as part of a positive half wave of input signal 10 230. Conversely, the complementary operation of negative half circuit 210 will cause similar parts of the positive half wave of input signal to be treated as part of the negative half waves. This may be acceptable and even preferable depending on the desired performance of a power amplifier according to the present invention. If this is not desired, offset block 211 may be coupled to the output of rectifier 215 to allow rectifier 215 to remove all parts of each negative half wave. Offset block 211 will then add the fixed offset to rectified signal 240.

15 [44] Returning to a description of power amplifier 200, main power supply 218 will emit some electro-magnetic radiation, which produces electro-magnetic interference (EMI) in nearby electronic devices. As is well understood, the amount of EMI produced by a switching regulator such as main power supply 218 depends on its switching rate. In order to reduce EMI, the switching rate of switch 246 is reduced by selecting a relatively low frequency for PWM control signal 242. The precise frequency chosen for PWM control signal (which is a fixed frequency signal) will depend on the characteristics of load 234, output signal 232 and energy which must 20 be delivered to properly power amplifier 204, among other criteria. A person skilled in the art will be capable of selecting a suitable frequency to balance these considerations with the need to reduce EMI emissions in a particular implementation of the present invention. Reducing the frequency of PWM control signal 242 and the switching rate of switch 246 has several effects.

[45] First, it increases the ripple in power signal V_{si} . To counteract this effect, the time constant of LC filter 250 is increased so that power signal V_s will be effectively smoothed despite the relatively low frequency at which switch 246 is operated.

[46] Second, the rate at which the magnitude of power signal V_s can rise or fall (i.e. the slew rate of power signal V_s) is reduced. If input signal 230 has a rapid increase in magnitude, amplifier 204 will require a rapid increase in its power supply to properly generate output signal 232 (i.e. V_{targ} will rise rapidly). Due to its slow slew rate, main power supply 218 may be unable to increase the magnitude of power signal V_s sufficiently quickly to power amplifier 236. Eventually, power signal V_s will rise to V_{targ} , up to a maximum of V_{max} volts. However, this will take a finite time.

[47] During this finite time period, additional power is provided by transient power supply 223 to amplifier 204 as follows. Transient detect block 219 operates to provide a digital transient signal 257. Peak detector 220 is coupled to rectifier 215 to receive rectified signal 240. Peak detector 220 provides a peak signal 252 corresponding to the peak envelope of the rectified signal 240 to differentiator 222. Differentiator 222 differentiates peak signal 252 to provide a differentiated signal 254. The magnitude of differentiated signal 254 at any point in time is indicative of the rate at which input signal 230 is changing. Comparator 255 compares differentiated signal 254 with a threshold voltage 256 to provide transient signal 257. When differentiated signal 254 exceeds threshold 256, transient signal 257 is high; otherwise, it is low.

[48] Switch 224 is responsive to transient signal 257 to selectively connect control circuit 216 to linear regulator 226. Linear regulator 226 may be a power MOSFET. The drain of linear regulator 226 is connected to power source 212 and the source of linear regulator 226 is connected to positive power input terminal 236. The gate of linear regulator 226 is connected to a terminal a of switch 224. Terminal b of switch 224 is coupled to control circuit 216 and terminal c of switch 224 is coupled to ground.

[49] When transient signal 257 is high, switch 224 engages transient power supply 224 by coupling the gate of linear regulator 226 to control terminal 243 (i.e.

terminal a is coupled to terminal b). At all other times, switch 224 couples the gate of linear regulator 226 to ground (i.e. terminal a is coupled to terminal c).

[50] Like control signal 242, control signal 244 is set by control circuit 216 so that transient power supply 223 will produce power signal V_i equal to V_{targ} . (It may be desirable to make power signal V_i slightly lower than power signal V_s . This is discussed further below.) Also, control signal 244 will be advanced compared to the time at which amplifier 204 will actually require the power level indicated by control signal 244. Control signal 244 is an analog signal, as opposed to control signal 242, which is a PWM signal.

[51] When the gate of linear regulator 226 is coupled to control terminal 243, it receives control signal 244. Linear regulator 226 is responsive to control signal 244 to provide power signal V_i to positive power input terminal 236. Linear regulator 226 has a very fast slew rate, and therefore its power signal V_i rises quickly to V_{targ} .

[52] Eventually, the magnitude of power signal V_s will rise to V_{targ} . At this point, power signal V_s will be sufficient to separately power amplifier 204. Until this time, it is necessary for switch 224 to keep transient power supply 223 engaged.. The period for which switch 224 must remain in this state will depend on the slew rate of main power supply 218 and on the rate of change of input signal 230. The slew rate of main power supply 218 may be calculated (or more likely, the slew rate may be pre-determined based on the maximum EMI that power amplifier 200 is permitted to emit and then main power supply 218 may be designed to have the selected slew rate). Threshold 256 is selected to correspond to this slew rate, so that main power supply 223 will be kept engaged by switch 224 until power signal V_s is able to rise to V_{targ} .

[53] Once transient power supply 223 is disengaged, it is important that peak detector 220 and differentiator 222 operate properly to ensure that linear regulator 224 may be engaged again if input signal 230 has another rapid rise in magnitude. This may be done by setting the discharge rate of peak detector 220 to correspond to the slew rate of main power supply 218 (which will depend on time constant of filter 250 and will also be affected by delays through the feedback network comprising amplifier 235, summer 237 and control circuit 216). This will ensure that the magnitude of peak signal 252 will fall as fast as power signal V_s , and will ensure that differential

signal 254 will exceed threshold 256 when input signal 230 rises too quickly for main power supply 218 to supply enough power to amplifier 204. Furthermore, this will also ensure that differential signal 254 will not fall below threshold 256 too quickly, causing linear regulator 226 to be disengaged before power signal V_s has risen to V_{targ} .

[54] As noted above, control signals 242 and 244 are set so that main power supply 218 and linear regulator 226 will provide power signals V_s and V_l of approximately the same magnitude (V_{targ}). This ensures that power signal V_t will have a smooth transition when linear regulator 226 is engaged by the operation of switch 224. When main power supply 218 is unable to raise its output power signal V_s sufficiently to power amplifier 204, differentiated signal 254 will exceed threshold 256. Very quickly thereafter, switch 224 will engage transient power supply 223. Since transient power supply 223 is configured to produce the same power signal V_{targ} as main power supply 218, and since linear regulator 226 is engaged very quickly after main power supply 218 becomes unable to produce the configured power signal V_{targ} , engaging transient power supply 223 will not cause a substantial jump in the total power signal V_t supplied to amplifier 204. Similarly, when transient power supply 223 is disengaged (when differentiated signal 254 falls below threshold 256), both transient power supply 223 and main power supply 218 will be generating the same power signal V_{targ} (i.e. $V_s = V_l = V_{targ}$). As a result, there will be a smooth transition in V_t when transient power supply 223 is switched off.

[55] Control signal 244 cannot be configured to produce a power signal V_l with a larger magnitude than power signal V_s (i.e. V_l cannot be larger than V_{targ}). If this occurs, power signal V_s produced by main power supply 218 may not reach V_{targ} before transient power supply 223 is disengaged, and therefore, may not be able to power amplifier 204 at that time. If power signal V_l exceeds the level to which main power supply 218 is being regulated by control signal 242 (i.e. V_l exceeds V_{targ}), then the magnitude of power signal V_t will be equal to the magnitude of power signal V_l . Since V_t exceeds V_{targ} , error signal 239 will indicate that V_{targ} may be lowered. Control circuit 216 will accordingly set control signal 242 to reduce power signal V_s .

Accordingly, control circuit 216 must ensure that control signal 242 remains constant

when transient power supply 223 is engaged. This may be done by setting control signal 244 to operate linear regulator 226 to produce power signal V_l with a slightly smaller magnitude than power signal V_s produced by main power supply 218 under the control of control signal 242 (i.e. V_l may be slightly lower than V_{targ}). Although this will cause a small transition in power signal V_l whenever transient power supply 223 is engaged, it will not have a substantial effect when transient power supply 223 is disengaged.

[56] Power amplifier 200 provides an efficient circuit for receiving input signal 230 to provide an amplified output signal 232. Amplifier 204, which performs the amplification of input signal 230, receives power from main power supply 218 and from linear regulator 226. At most times, amplifier 204 receives power only from main power supply 218 and transient power supply 223 is disengaged by grounding its control terminal (i.e. its gate). The power output signal V_s of main power supply 218 is configured to follow and slightly exceed the power V_{req} required by amplifier 204 to generate output signal 232. This reduces power dissipation in amplifier 204 and the overall power consumption of power amplifier 200. The switching frequency of main power supply 218 is kept intentionally low to reduce EMI generation. This causes main power supply 218 to have a slow slew rate and main power supply 218 may not be able to provide sufficient power to amplifier 204 to produce output signal 232. When such a condition occurs, transient power supply 223 is engaged. Transient power supply 223 has a fast slew rate, allowing it to quickly provide the power V_{req} required by amplifier 204 to produce output signal 232. Transient power supply 223 is kept engaged for a period sufficient to allow main power supply 218 to increase its power supply signal V_s to V_{req} , and then transient power supply 223 is disengaged.

[57] Reference is next made to Figure 3, which is a block diagram of a third power amplifier 280 according to the present invention. Power amplifier 280 is similar to power amplifier 200 except that the control signals for main power supply 218 and transient power supply 223 are generated by separate control circuits. In addition to the components of power amplifier 200, power amplifier 280 has a first control circuit 282, a second control circuit 283, an amplifier 294 and a summer 286.

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[58] Amplifier 294 is coupled to main power supply 218 to receive power signal V_s . Amplifier 294 reduces the range of power signal V_s and produces a reduced power signal V_{sr} , which has a range comparable to that of rectified signal 240. Summer 286 is coupled to rectifier 215 and to amplifier 294 to receive rectified signal 240 and reduced power signal V_{sr} . Summer 286 produces an error signal 288 which indicates the difference between the power V_{req} required to produce output signal 232 (i.e. as represented by rectified signal 240) and the power signal V_s being supplied by main power supply 218 to amplifier 204. Control circuit 282 is coupled to summer 286 to receive error signal 288. Control circuit 282 provides a PWM control signal 290 in response to error signal 288 to control switch 246 of main power supply 218.

[59] Amplifier 235 is coupled to terminal 236 to receive power signal V_t and operates as in power amplifier 200 to produce reduced power signal V_{tr} . Summer 237 is coupled to rectifier 215 to receive rectified signal 240 and to amplifier 235 to receive reduced power signal V_{tr} and operates as in power amplifier 200 to produce error signal 239. Control circuit 284 receives control signal 239 and produces an analog control signal 292, which is similar to control signal 244 of power amplifier 200. Switch 224 may couple control signal 292 to the gate of linear regulator 226, when transient power supply 223 is required to supply power signal V_l to amplifier 204, in the same manner as described above in relation to power amplifier 200. Power signals V_l and V_s are diode or'd through diode 251 to produce power signal V_t .

[60] By generating control signals 290 and 292 separately through independent feedback paths and control circuits 282 and 284, respectively, main power supply 218 and transient power supply 223 may be independently controlled. In particular, by referencing control signal 290 to the output of main power supply 218 only, it is not necessary to ensure that power signal V_l does not exceed the voltage V_{targ} to which main power supply 218 is being regulated, as is required in the case of power amplifier 200.

[61] Reference is next made to Figure 4, which illustrates a fourth power amplifier 300 according to the present invention. Power amplifier 300 illustrates the use of a power amplifier based on power amplifier 200 to power several channels

simultaneously. Power amplifier 300 also illustrates the use of overload detectors to protect the amplifiers of power amplifier 300.

[62] Power amplifier 300 has two input terminals 302a, 302b, two amplifiers 304a, 304b, a positive half circuit 308 and a negative half circuit 310. Power amplifier 300 is configured to amplify input signals 330a and 330b, which are received at input terminals 302a and 302b, respectively. Input signals 330a and 330b are two separate input signals and may be two channels in an audio system. For example, input signals 330a and 330b may be the left and right channels in a standard audio system.

[63] Amplifiers 304a and 304b are coupled to input terminals 302a and 302b to receive input signals 330a and 330b. Amplifier 304a and 304b provide amplified output signals 332a and 332b, which correspond to input signal 302a and 302b, to loads 334a and 334b.

[64] Offset block 311a, frequency compensation block 314a and rectifier 315a, which comprise a first input signal compensation block 305a, are coupled to input terminal 302a in the same manner as offset block 211, frequency compensation block 214 and rectifier 215 are coupled to input terminal 202 of power amplifier 200. Rectifier 315a provides a rectified signal 340a corresponding to input signal 330a at terminal 341a. Similarly, offset block 311b, frequency compensation block 314b and rectifier 315b, which comprise a second input signal compensation block 305b, are coupled to input terminal 302b and rectifier 315b provides a rectified signal 340b corresponding to input signal 330b at terminal 341b. Terminals 341a and 341b are coupled to terminal 341 through diodes 360a and 360b. Rectified signals 340a and 340b are diode-or'd by diodes 360a and 360b, providing a rectified signal 340 at terminal 341, which corresponds generally to either the highest magnitude of signals 330a and 330b at any particular time. Offset blocks 311a and 311b may be configured to compensate for the diode drops caused by diodes 360a and 360b in rectified signals 340a and 340b.

[65] Rectified signal 340 generally corresponds to highest of the power levels required by either amplifier 304a or 304b to produce output signal 332a or 332b. Summer 368 receives rectified signal 340 and a combined overload detect

signal 366, which is explained below and provides an adjusted rectified signal 370, which is used to produce power signal V_t at positive power input terminal 236 in the same manner as rectified signal 240 is used in power amplifier 200.

[66] Amplifier 304a is coupled to power input terminal 236 through an overload detect block 362a. Amplifier 304a receives power signal V_t and provides output signal 332a. Similarly amplifier 304b is coupled to power input terminal 236 through an overload detect block 362b and provides output signal 332b. Overload detect blocks 362a and 362b are configured to detect overload conditions in their associated amplifiers 304a and 304b. For example, overload detect blocks 362a and 362b may be configured to detect over-current, over-temperature or other overload conditions. If overload detect block 362a detects such a condition in its associated amplifier 304a, then overload detect block 362a will produce an overload signal 366a, which corresponds to the magnitude of the overload condition detected. Similarly, overload detect block 362b will produce an overload signal 366b if an overload is detected in amplifier 304b. Overload signals 366a and 366b are diode or'd through diodes 364a and 364b to produce a combined overload signal 366, which is subtracted from rectified signal 340 to produce adjusted rectified signal 343. Adjusted rectified signal 343 is used to control the magnitude of power signal V_t . In this way, overload detect blocks 362a and 362b operate to reduce power signal V_t to protect amplifier 304a and 304b when an overload occurs.

[67] Since input signals 330a and 330b are independent of one another, they may have different magnitudes at any point in time. Accordingly, output signals 332a and 332b will have different amplitudes and amplifiers 304a and 304b will have different power requirements. Power signal V_t is large enough to power the amplifier 304a or 304b with the largest power requirement at any particular (assuming that no overload condition exists). As a result, one of the amplifiers will receive more power than it requires and will dissipate the excess power.

[68] It has been found that the dissipation of this excess power in one of the amplifiers 304a or 304b does not substantially reduce the average efficiency of power amplifier 300. Reference is made to Figure 5, which shows output signals 322a and 322b and power signal V_t . In the portion of the signals shown, output signal 322b is

experiencing a peak at time t_1 . Output signal 322a is at a typical or average level. A typical audio signal, such as a movie soundtrack or music, may have a peak-to-average magnitude ratio of 8:1 or higher. At time t_1 , output signal 322a may have a current of 2 amps and a magnitude of 5 volts while output signal 322b may have a current of 14 amps and a magnitude of 35 volts. (Output signal 322b has 49 times more power than output signal 322a). Typically, output signal V_t may have an average magnitude of 41 volts (which is selected to account for any ripple in output signal V_t to power the components of both amplifiers 204a and 204b and to provide reasonable headroom in the amplifier 204a or 204b with the higher power requirements) when amplifiers 304a and 304b are called on to produce these output signals 332a and 322b. Accordingly, output signal 322a has a headroom of 36 volts and will dissipate 72 watts of power (i.e. 36 volts x 2 amps). Output signal 322b has a headroom of 6 volts and will dissipate 84 watts (i.e. 6 volts x 14 amps). Amplifier 304b will therefore actually exhibit a high power loss, even though amplifier 304a has a much larger headroom. As a result, the large headroom created in amplifier 304a due to the peak of output signal 304b does not substantially increase the average power dissipated by power amplifier 300 in comparison to the power dissipated in amplifier 304b at the same time. Furthermore, peaks in a typical musical selection or a movie soundtrack occur relatively infrequently (and often occur on several channels simultaneously) and since the average level of a typical selection is generally less than 1/8th the level of the peaks in the selection, sharing main power supply 218 and transient power supply 223 between more than one amplifier does not result in a substantial change in the overall efficiency of power amplifier 300.

[69] Power amplifier 300 allows main power supply 218 and transient power amplifier 223 to be shared between two channels having separate inputs, amplifiers and outputs. The design of power amplifier 300 is not limited to two channels and may be used to power any number of channels. For example, power amplifier 300 could be adapted to power 6 or more channels simultaneously for use with a typical "surround sound" soundtrack for a movie, which may have 5 or more audio channels and 1 or more additional sub-woofer channels.

10 [70] Reference is next made to Figure 6, which illustrates a fifth embodiment of a power amplifier 400 according to the present invention. Power amplifier 400 is similar to power amplifier 200. Power amplifier 400 has an input terminal 202, an amplifier 204, an output terminal 206, a positive half circuit 408 and a negative half circuit 410. In addition to the structure defined above in relation to positive half circuit 208 of power amplifier 200, positive half circuit 408 includes a low voltage power supply 402 and a diode 404. Control circuit 216 of power amplifier 200 has been replaced with control circuit 416. Main power supply 218 of power amplifier 200 has been replaced with main power supply 418, which is a switching power regulator with an LC filter 450.

[71] Reference is briefly made to Figure 2. As noted above, the switching speed of main power supply 218 is kept intentionally low to reduce the amount of EMI generated by main power supply 218. To reduce the amount of ripple in power signal V_s (as compared to the relatively large ripple in power signal V_{si}), the time constant of filter 250 is increased. Although this provides a smoother power signal V_s , it also further reduces the slew rate of main power supply 218, thereby preventing power signal V_s from closely following output signal 232.

[72] Referring again to Figure 6, it is therefore desirable to decrease the time constant of filter 450 to allow power signal V_s to follow the output signal 232 closely. This has the disadvantage that the ripple produced in power signal V_{si} may not be effectively removed from power signal V_s . Depending on the time constant of filter 250, the ripple in power signal V_s may be quite large. The selection of an optimal time constant will depend on the nature of input signal 230, the desired efficiency of power amplifier 400 and the desired EMI emission level for power amplifier 400. The selection of a low time constant for filter 450 has three adverse consequences.

[73] First, when the magnitude of power signal V_s is relatively low, the ripple in power signal V_s will produce a proportionally large amount of energy to be stored in (and later dissipated from) capacitor 451 of filter 450. The magnitude of the ripple in power signal V_s will be relatively constant regardless of the magnitude of power signal V_s . The energy stored in capacitor 451 is equal to $1/2 CV_s^2$. When power signal V_s has a relatively low magnitude (which will be the case much of the time, since peaks

in a typical music signal are relatively infrequent), the ripple in power signal V_s will be relatively large, and will therefore cause a proportionally larger excess amount of energy to be stored in capacitor 451 during each pulse created in power signal V_{si} by the closing and opening of switch 246. This excess energy is later dissipated and is essentially wasted. This increases the power consumption of power amplifier 400.

[74] Second, the difference between the voltage to which power signal V_s is regulated (V_{targ}) and the voltage required by amplifier 204 to produce output signal 230 must be increased to ensure that power signal V_s is sufficient at all times to power amplifier 204. The increased average headroom between power signal V_s and the power V_{req} required by amplifier 204 results in increased power dissipation in the amplifier 204 and a higher overall power consumption for power amplifier 400. This may be done by increasing the offset added into input signal 230 by offset block 211 or by modifying control circuit 216.

[75] Third, the ripple in power signal V_s may actually be coupled to output signal 232 through amplifier 204 and may be audible, depending on the frequency of the ripple (which in turn will depend on the frequency at which switch 246 is operated). To reduce the effect of this ripple on power signal V_s when the magnitude of power signal V_s is low, it may be desirable to eliminate the use of main power supply 418 when output signal 232 is relatively low.

[76] This is accomplished by using low voltage power supply 402 when the magnitude of output signal 232 is relatively small. Low voltage power supply 402 is coupled to positive power supply terminal 236 and provides a fixed voltage DC power signal V_{LV} to amplifier 204 at all times. Power signal V_{LV} is diode-or'd with power signal V_s and power signal V_i through diodes 404 and 251. In power amplifier 400, at any particular time, power signal V_t delivered to positive power input terminal 236 is equal to the highest of power signals V_i , V_s and V_{LV} .

[77] Control circuit 416 of power amplifier 400 may be configured to keep switch 246 open when the magnitude of output signal 232 is less than the magnitude of power signal V_{LV} . This may be done by setting control signal 442 to 0 during these periods and it effectively eliminates the proportionally high energy loss which would otherwise occur when power signal V_s has a low magnitude. Furthermore, this

eliminates the generation of EMI by switching regulator 232 during these periods when it is effectively disengaged. Control circuit 416 will be able to determine when to engage and disengage main power supply 418 based on error signal 239. Since power signal V_t will have a minimum magnitude of V_{LV} , error signal 239 may be negative when input signal 230 is very small (and correspondingly amplifier 204 requires little power to generate output signal 230. When error signal 239 is negative (or below a selected threshold which may be built into control circuit 416), control circuit 416 will disengage main power supply 418.

[78] Since power signal V_{LV} has a fixed magnitude (even during negative half waves of input signal 230), it becomes the minimum magnitude that power signal V_t can have. This does not substantially reduce the efficiency power amplifier 400 because the large ripple introduced into power signal V_s by decreasing the time constant of main power supply 218 essentially forces power signal V_s (and hence power signal V_t) to have a minimum average at least as large as one-half of the peak-to-peak magnitude of the ripple.

[79] Reference is made to Figure 7, which illustrates an average positive half wave of output signal 232 and power signal V_s , V_{LV} and V_t during the corresponding period. The magnitude V_{LV} of low voltage power supply 402 is selected to be a fraction of the average magnitude V_{s-avg} of power supply V_s during periods when output signal 232 is at an average level (i.e. a period during which no peaks occur). (During such periods, transient power supply 223 will generally not be engaged.) During the period shown in Figure 7, transient power supply 223 is disengaged. Between times t_2 and t_3 and between times t_4 and t_5 , the magnitude of output signal 232 is less than the magnitude of power signal V_{LV} and power signal V_t is equal to power signal V_{LV} .

As noted above, control circuit 216 may be configured to disengage main power supply 418 is disengaged by setting control signal 442 to 0. In power amplifier 400, control circuit 416 is configured to disengage main power supply 418 when the magnitude of output signal 232 is less than a selected threshold V_d . When the magnitude of output signal 232 approaches threshold V_d , main power supply 418 is engaged by control circuit 416 to produce power signal V_s . Threshold V_d must be selected to ensure that main power supply 418 is engaged whenever power signal

V_{LV} would be insufficient to power amplifier 204 to produce output signal 232. In selecting threshold V_d , the desired headroom (defined above as $V_{targ} - V_{req}$) must be taken into account. When main power supply 418 is engaged, power signal V_t will be equal to the higher of power signal V_{LV} and V_s .

5 [80] The use of low voltage power supply 402 in power amplifier 400 allows a filter 450 with a relatively short time constant to be used, allowing power signal V_s (and consequently power signal V_t) to more closely follow output signal 232 than is possible in power amplifier 200. Furthermore, the use of low voltage power supply 402 allows main power supply 418 to be disengaged during periods when it would
10 have a large proportional power loss and would generate relatively high EMI emissions.

[81] Reference is briefly made to Figure 2. PWM control signal 242 consists of a series of pulses which may have differing pulse widths. The rising edges of successive pulses (assuming that a pulse is measured between a rising edge and a falling edge) are spaced apart by a fixed time period. Switch 246 is closed when PWM control signal 242 is high and switch 246 is open when PWM control signal 242 is low. The opening and closing operations of switch 246 produce an essentially square wave power signal V_{si} . Transitions in PWM control signal 242 occur without regard to the current flowing through switch 246. As a result, switch 246 may be opened while substantial currents are flowing through it, creating EMI emissions and high switching stresses and switching losses on the components on main power supply 218. (These currents are drawn by amplifier 204 to produce output signal 232.) These inefficiencies may be alleviated by opening and closing switch 246 only when the current being drawn from main power supply 218 is zero or almost zero.

25 [82] Reference is next made to Figure 8 which is a block diagram of a sixth embodiment of a power amplifier 500 according to the present invention. Power amplifier 500 is similar to power amplifier 400, except for the configuration and structure of its control circuit 516 and main power supply 518. Power amplifier 500 has an input terminal 202 and an amplifier 204 which operate as in power amplifiers
30 200 and 400 to produce an output signal 232 at a terminal 206. Load 234, which may be a speaker, receives output signal 232. Power amplifier 500 also has a positive

half circuit 508, which supplies power to amplifier 204 at a power terminal 236 during positive half waves of input signal 230, and a negative half circuit 510 which has the same structure as positive half circuit 508 and a complementary operation to supply power to amplifier 204 during negative half waves of input signal 230.

5 **[83]** Positive half circuit 508 is similar to positive half circuit 408 of power amplifier 400, except that control circuit 408 has been replaced with a pulse density modulation (PDM) control circuit 508 and main power supply 418 has been replaced with a main power supply 518 which is a resonant switching power regulator. Main power supply 518 may be any type of resonant switching regulator such as a zero-current-switching (ZCS) converter, a zero-voltage-switching (ZVS) converter, a zero-voltage-switching quasi-resonant converter (ZVS-QRC), a zero-voltage-switching multi-resonant converter (ZVS-MRC), a constant-frequency, a zero-voltage-switching quasi-resonant converter (CF-ZVS-MRC). Such converters are described in U.S. Patent 4,720,668, entitled "Zero Voltage Switching Quasi Resonant Converters" and in U.S. Patent 5,479,337, entitled "Very Low Power Loss Amplifier for Analog Signals Utilizing Constant-Frequency Zero-Voltage Switching Multi-Resonant Converter". Such regulators have the advantage of lower EMI emissions and lower switching losses than the non-resonant main power supplies 218, 318 and 418 described above in respect of power amplifiers 200, 280, 300 and 400.

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20 **[84]** Main power supply 518 is a zero-current-switching (ZCS) switching regulator. Main power supply 518 includes a switch 546, diodes 547, 548 and a LC resonant tank 570 comprised of an inductor 572 and a capacitor 574, and an LC filter 550.

25 **[85]** PDM control circuit 516 receives error signal 239 and provides a PDM control signal 542 at terminal 241 and second control signal 244 at terminal 243, which is the same as second control signal 244 provided by control circuit 216 of power amplifier 200. However, PDM control signal 542 is different from control signal 242, which is a pulse width modulated signal. Instead, PDM control signal 542 consists of a series of identical "high" pulses – each high pulse has an identical pulse length or a "constant on-time" (and an identical magnitude). After each pulse (i.e. after its falling edge), another pulse will not begin, and PDM control signal 542

will remain low, for a selected "minimum off-time". The pulses may be spaced apart by different periods, depending on the magnitude of the target power signal V_{targ} needed to power amplifier 204 indicated by rectified signal 240. When a higher magnitude power signal is required, the time period between pulses is reduced, and vice versa. As a result, PDM control signal 542 has a "variable off-time" between pulses.

[86] Main power supply 518 receives PDM control signal 542 and produces a power signal $V_{\text{s-res}}$ in response. Power signal $V_{\text{s-res}}$ is analogous to power signal V_{s} produced by main power supply 218 of power amplifiers 200, 280, 300 and 400.

Power signal $V_{\text{s-res}}$ is diode-or'd with power signal V_{I} and V_{LV} to produce power signal V_{t} , which is received by amplifier 204 at terminal 236.

[87] Switch 546 is preferably a MOSFET type transistor which receives PDM control signal 542. Alternatively, another semiconductor device such as an IGBT, BJT or an SCR may be used. Switch 546 is open (i.e. the MOSFET is "off") when PDM control signal 542 is low and is closed (i.e. the MOSFET is "on") when PDM control signal 542 is high. As is known, a MOSFET may conduct in both directions between its drain and its source when it is on and may allow current to flow from its source to its drain (typically considered the reverse direction) when it is off. Diode 547 is installed in series with switch 546 to prevent the flow of current in the reverse direction (i.e. from source to drain) of switch 546.

[88] Reference is made to Figure 9, which illustrates the current flowing in switch 546. If switch 546 is closed at a time t_6 , LC resonant tank 570 causes a substantially sinusoidal pulse 576 to be produced at the cathode of diode 548. Sinusoidal pulse 576 begins at about time t_6 and ends at about time t_7 , and lasts for a time period t_8 . The length of time period t_8 depends on the values of inductor 572 and capacitor 574. Time t_6 may be determined in known manner by calculation or experimentation. At time t_6 and again at time t_8 , the current in switch 546 is zero, and accordingly, by closing switch 546 at time t_6 and then opening switch 546 at time t_7 , the EMI emissions and switching losses of switch 546 may be substantially reduced.

[89] The constant on-time of PDM control signal 542 is selected to exceed time period t_8 , so that when switch 546 is opened at time t_7 (or later), switch 546 will

essentially open a circuit which is carrying no current. During pulse 576, capacitor 574 will have become charged, and when switch 546 is opened, capacitor 574 will have no voltage across it but will have a charge on it. After switch 546 is opened, this charge is discharged into filter 550. The minimum off-time of PDM control signal 546 is selected to allow the charge on capacitor 574 to be essentially completely discharged. If the minimum off-time is too short, a charge will build up on capacitor 574 and the resonant operation of main power supply 518 will be degraded. The structure of PDM control circuit 516 is described below (Figure 11).

[90] Reference is again made to Figure 8. As switch 546 opens and closes in response to PDM control signal 542, a series of pulses 576 are generated, forming a power signal V_{si-res} . LC filter 550 smooths power signal V_{si-res} to produce power signal V_{s-res} . The magnitude of power signal V_{s-res} during a particular time period will depend on the density of pulses 576 in power signal V_{si-res} . Power signal V_{s-res} is diode-or'd with power signal V_i and V_{LV} by diodes 251 and 404 to form power signal V_t , which is provided to power amplifier 204 at terminal 236.

[91] Referring briefly to Figure 2, PWM control signal 242 may have a duty cycle ranging from 0% to 100%. As a result, power signal V_s may range from 0 volts to the magnitude V_{max} of power source 212 (ignoring the negligible voltage drops across the components of main power supply 218).

[92] Since PDM control signal 542 has a minimum off-time between each pulse 572 (Figure 8), switch 546 cannot have a duty cycle of 100%. As a result, power signal V_{s-res} has a lower magnitude than the magnitude $V_{max-res}$ of power supply 512 (which is analogous to power source 212). To allow power signal V_{s-res} to have the same magnitude as power signal V_s of the power amplifiers described above, the magnitude $V_{max-res}$ of power supply 512 must be higher than the magnitude V_{max} of power source 212 (Figure 2).

[93] Since each pulse 576 produced by switch 546 will be identical, each pulse 576 will transfer a fixed amount of energy first into capacitor 574 and then into filter 550. The magnitude of power signal V_{s-res} will depend entirely of the density of pulses 576 (i.e. on the variable off-time between pulses). When a low power signal V_{s-res} is required, the density of pulses may be quite low and the frequency of the

pulses may actually be in the audio band. Also, if the density of pulses is low, a large ripple may be seen in power signal $V_{s\text{-}res}$, and if filter 550 has a desirable low time constant (which allows power signal $V_{s\text{-}res}$ to more closely follow the output signal 232, as described above in relation to power signal V_s of power amplifier 400), power signal $V_{s\text{-}res}$ may also have a corresponding large ripple.

[94] In order to reduce the effects of this large ripple (which are described above in relation to power amplifier 400), low voltage power supply 402 is included in power amplifier 500, in the same manner as in power amplifier 400. The use of low voltage power rail 402 is not necessary, particularly where the magnitude of output signal 232 will be relatively high, and the disadvantages of high ripple (which are more disadvantageous at a low output level) will not be substantial. If low voltage power rail 402 is included in power amplifier 500, PDM control circuit 516 may be configured to disengage main power supply 518 when the magnitude of output signal 232 is expected to be less than threshold V_d (Figure 7).

[95] In this way, power signal V_s may be formed using PDM control circuit 542 and main power supply 518 while generating substantially less EMI than is generated by PWM control circuit 242 and main power supply 218.

[96] Reference is next made to Figure 10, which illustrates a seventh embodiment of a power amplifier 600 according to the present invention. Power amplifier 600 has an input terminal 202, an amplifier 204 and an output terminal 206 which are connected and operate in the same manner as in power amplifier 200. Power amplifier 600 has positive half circuit 608 and a negative half circuit 610, which is similar in structure and complementary in operation to positive half circuit 608. Positive half circuit 608 is similar to positive circuit 508 of power amplifier 500, with three exceptions. First, positive half circuit 608 does not include low voltage power supply 402, which was included in positive half circuit 508 and described above in relation to power amplifier 400. Second, positive half circuit 608 includes an overload detect block 362, the coupling and operation of which described above in relation to power amplifier 300. Third, positive half circuit 608 includes a rectifier 680, a summer 681, an amplifier 688, a summer 682 and a post regulator 684.

[97] Rectifier 680 is coupled to offset block 211 to receive offset input signal 231 and to provide a rectified input signal 633, which corresponds to the power level required by amplifier 204 to produce output signal 232 in response to input signal 230. Rectified input signal 633 differs from rectified signal 240 in that no frequency compensation block (such as frequency compensation block 214) is used to produce rectified input signal 633. As a result, rectified input signal 633 does not have the phase lead effect of rectified signal 240 and the magnitude of rectified input signal 633 corresponds to the power required at a particular time, rather than a slightly later time.

[98] Summer 681 is coupled to rectifier 680 to receive rectified input signal 633 and to overload detect block 362 (at a terminal 363) to receive overload detect signal 366. Summer 681 provides a regulation signal 690 equal to the difference between rectified input signal 633 and overload detect signal 366. Regulation signal 690 corresponds to rectified input signal 633 reduced by any excess power which could damage amplifier 204.

[99] Amplifier 688 receives regulation signal 690 and provides an amplified regulation signal 692, which corresponds to regulation signal 690 but has a magnitude range which corresponds to the magnitude range of power signal V_t .

[100] Post regulator 684 may be a MOSFET type transistor, as shown in Figure 9. The drain of post regulator 684 is coupled to the cathode of diode 251 to receive power signal V_t . The source of post regulator 684 is coupled to positive power input terminal 236 to provide a regulated power signal V_{t-reg} to amplifier 204. The gate of post regulator 684 is coupled to summer 682. Summer 682 is coupled to amplifier 688 to receive amplified regulation signal 692 and to positive power input terminal 236 to receive power signal V_{t-reg} . Summer 682 provides a regulator error signal 686 which is equal to the difference between amplified rectified input signal 683 and power signal V_{t-reg} . Regulator error signal 686 reflects the difference between the power required by amplifier 204 to produce output signal 232 and the power actually being provided to amplifier 204 at positive power input terminal 236. If regulator error signal 686 is positive, then amplifier 204 is receiving more power than is required (or more power than is safe, based on overload detect signal 366). Post regulator 684

reduces power signal V_t received at the a drain of post regulator 684 and provides a smaller power signal V_{t-reg} to amplifier 204.

[101] Normally, amplified regulation signal 692 will be configured to maintain post regulator 684 in a saturated condition so that power signal V_{t-reg} is essentially equal to power signal V_t . The offset added by offset block 211 to input signal 230 to produce offset input signal 231 may be sufficient to produce this result. However, the amplification factor of amplifier 688 may also be used to ensure that post regulator 684 is normally saturated. However, when an overload condition is detected by overload detector 362, regulation signal 690 and amplified regulation signal 692 will fall quickly and post regulator 684 will act to limit power signal V_{t-reg} . Post regulator 684 operates as a linear regulator, and preferably, it is highly responsive to changes in its gate voltage. Post regulator may be a power transistor, such as a power MOSFET, IGBT, BJT, or any other device which may be used a regulator.

[102] In this way post regulator 684 is able to quickly reduce the power signal V_{t-reg} provided to amplifier 204 at positive power input terminal 236. Post regulator 684 is particularly useful when amplifier 204 is implemented as a power integrated circuit which might be damaged by an overload in microseconds.

[103] As noted above, positive half circuit 608 does not include low voltage power supply 402. In addition to regulating the level of power supply V_{t-reg} when an overload occurs, post regulator 684 also smooths power signal V_t so that power signal V_{t-reg} has less ripple than power signal V_t . As noted above in relation to power amplifier 400, one reason for using low voltage power supply 402 to eliminate the use of main power supply 218 (or resonant switching regulator 518) was to reduce eliminate the problem of a relatively large ripple on power signal V_t when power signal V_t had a relatively low magnitude. Since this ripple will be reduced by post regulator 684, the need for low voltage power supply 402 is reduced. If desired, low voltage power supply 402 may be incorporated into power amplifier 600 and a person skilled in the art will be capable of doing so.

[104] Power amplifiers 200, 280, 300, 400, 500 and 600 utilize a feedback control system to ensure that power signal V_t (or V_{t-reg} in power amplifier 600) provides sufficient power to amplifier 204 to allow it to produce output signal 232 without

excessive headroom. This feedback circuit will now be described, in the context of power amplifier 600, with reference to Figures 11 and 12.

[105] Figure 11 illustrates terminal 217 (Figure 10), at which rectifier 215 produces rectified signal 240, summers 237 and 368, peak detector 220, differentiator 222, switch 224, part of PDM control circuit 516, a bias point network 702 and a rectified signal amplification network 704.

[106] Bias point network 702 comprises resistor R_1 , R_2 , R_3 and a zener diode D_1 . Resistor R_1 is coupled between ground and a terminal 706. Resistor R_2 is coupled between terminal 706 and a terminal 708. Resistor R_3 is coupled between terminal 708 and the most negative point of power amplifier 600 (Figure 9). The most negative point of power amplifier 600 will, in general, be substantially more negative than the ground of power amplifier 600 and a person skilled in the art will be capable of selecting such a point. Zener diode D_1 is coupled between terminal 708 and ground. Resistors R_1 and R_2 form a voltage divider across zener diode D_1 so that terminal 706 will have a voltage less than ground (i.e. if zener diode D_1 has a zener voltage of 5 volts, $R_1 = 10\text{ k}\Omega$ and $R_2 = 25\text{ k}\Omega$, then terminal 706 will have a voltage of -1.43 volts). The voltage at terminal 706 provides a bias voltage for transistors Q_2 and Q_3 , which are described below. In general, the bias voltage will be set to be less than -0.7 volts.

[107] Summers 237 and 368 are combined and implemented as a single summing network 708. Summing network 708 comprises transistors Q_1 , Q_2 , Q_3 and Q_4 , resistors R_4 , R_5 , R_6 and R_7 , a diode D_2 and a capacitor C_1 . The emitter of pnp transistor Q_1 is coupled to terminal 236 through resistor R_4 to receive power signal V_{t-reg} . Power signal V_{t-reg} is converted into a current signal i_t by resistor R_4 . The base of transistor Q_1 is coupled to ground, and accordingly, a current signal i_o is provided at the collector of transistor Q_1 . Since the base of transistor Q_1 is coupled to ground, current signal i_o will generally be equal current signal i_t (so long as power signal V_{t-reg} exceed ground by 0.7 volts). Current signal i_o represents the magnitude of output signal V_{t-reg} at any particular time.

[108] The collector of transistor Q_1 is coupled to the collector of diode-connected transistor Q_3 . The collector of transistor Q_3 is also coupled to terminal 363 through diode D_2 to receive overload detect signal 366, which is a current signal and is shown as current signal i_d . The emitter of transistor Q_3 is coupled ground through a resistor R_6 . Terminal 363 is coupled to ground through capacitor C_1 which operates to integrate and smooth overload detect signal 366. Diode D_2 ensures that no current flows into terminal 363 from summing network 708. Current signal i_o and overload detect signal i_d are summed at the collector of transistor Q_3 to form a current signal i_{sum} , which flows from the collector to the emitter of transistor Q_3 .

[109] Transistor Q_4 is coupled to transistor Q_3 as a current mirror. The base of transistor Q_4 is coupled to the base and collector of transistor Q_3 . The emitter of transistor Q_4 is coupled to ground through resistor R_7 . A current equal to i_{sum} , flows from the collector to the emitter of transistor Q_4 . This current i_{sum} is drawn from a terminal 710.

[110] The emitter of pnp transistor Q_2 is coupled to terminal 217 through resistor R_5 to receive rectified signal 240, which corresponds to the amount of power required by amplifier 204 to produce output signal 232 (Figure 10). The base of transistor Q_2 is coupled to terminal 706 and the emitter of transistor Q_2 is coupled to terminal 710. Resistor R_5 converts rectified signal 240 into a current signal i_r , which flows from the emitter to the collector of transistor Q_2 , as long as rectified signal 240 exceeds the bias voltage at terminal 706 by 0.7 volts. Since rectified signal 240 is always above 0 volts, and since the bias voltage will generally be selected to less than -0.7 volts, current i_r will flow when ever rectified signal 240 is non-zero.

[111] A current signal i_e , flows out from terminal 710 to terminal 712. Current signal i_e will be equal to current i_r less current i_{sum} . Current signal i_e is error signal 239 (Figures 1 and 9) and corresponds to the difference between the power that amplifier 204 requires and the power that it is presently receiving.

[112] One part of PDM control signal 516 includes transistor Q_7 . The base of transistor Q_7 is coupled to terminal 712. The collector of transistor Q_7 is coupled to a voltage source V_{cc} and the emitter of transistor Q_7 is coupled to terminal 243.

Transistor Q_7 is coupled as an emitter-follower and simply buffers error signal 239 (or i_e) and provides control signal 244 (equal to error signal 239) at terminal 243.

[113] Rectified signal amplification circuit 704 includes transistors Q_5 and Q_6 and resistors R_8 and R_9 . The emitter of pnp transistor Q_5 is coupled to terminal 217 through resistor R_8 . The base of transistor Q_5 is coupled to terminal 706. The collector of transistor Q_5 is coupled to terminal 714. Resistor R_9 is coupled between terminal 714 and ground. Resistor R_9 is selected double the resistance of resistor R_8 . The base of transistor Q_6 is coupled to terminal 714. The collector of transistor Q_6 is coupled to a voltage source V_{cc} and the emitter of transistor Q_6 is coupled to a terminal 716. Resistor R_8 and transistor Q_5 operate in the same manner as (and may actually be matched to) resistor R_5 and transistor Q_2 to provide a current signal i_p (which may be equal to current signal i_r) at the collector of transistor Q_5 . Current signal i_p corresponds to the magnitude of rectified signal 240. Current signal i_p flows through resistor R_9 to ground, with the result that the voltage at terminal 714 is equal to 2 times the voltage of rectified signal 240 at any particular time. Transistor Q_7 is configured as an emitter-follower and simply buffers the voltage at terminal 714 to a voltage signal V_{rect} (equal to 2 times rectified signal 240) at terminal 716.

[114] Peak detector 220 consists of a capacitor C_9 and a resistor R_{10} coupled in series between terminal 716 and ground. Peak detector 220 operates in known manner to provide peak signal 252 at terminal 718.

[115] Differentiator 222 consists of a capacitor C_3 and resistor R_{11} and R_{12} . Capacitor C_3 and resistor R_{11} are coupled in series between terminal 718 and ground. Resistor R_{12} is coupled between the junction of capacitor C_3 and resistor R_{11} and a terminal 720. Differentiator 222 operates in known manner to provide differential signal 254 at terminal 720.

[116] Switch 224 comprises transistors Q_8 and Q_9 and resistors R_{13} , R_{14} and R_{15} . The base-emitter junction of transistor Q_8 is coupled between terminal 720 and ground. The collector of transistor Q_8 is coupled to the base of transistor Q_9 through resistor R_{14} . Resistor R_{14} and the base of transistor Q_9 are coupled to voltage source V_{cc} through resistor R_{13} . The emitter of pnp transistor Q_9 forms terminal b of switch 224 and is coupled to terminal 243 to receive control signal 244. The collector of

transistor Q_9 forms terminal a of switch 224. Terminal a is coupled to the gate of linear regulator 226 (Figures 3 and 10). The collector of transistor Q_9 is coupled to ground through resistor R_{15} . The ground side connection of resistor R_{15} forms terminal c of switch 224.

[117] Switch 224 operates as follows. When differentiated signal 254 exceeds 0.7 volts, the base-emitter junction of transistor Q_8 is forward biased, and transistor Q_8 turns on. Resistor R_{13} and R_{14} form a voltage divider between voltage source V_{cc} and ground, thereby setting a base voltage for pnp transistor Q_9 . When control signal 244 (at the collector of transistor Q_9) exceeds this base voltage, transistor Q_9 conducts and couples terminal 243 (and terminal b) to terminal a, thereby allowing control signal 244 to control linear regulator 226. If differentiated signal 254 does not exceed 0.7 volts, then transistor Q_8 does not conduct and the base of transistor Q_9 is pulled up to V_{cc} through resistor R_{13} . Voltage source V_{cc} is selected so that control signal 244 will not exceed it and therefore, transistor Q_9 will not conduct. Terminal a will be pulled down to ground through resistor R_{15} , and will be effectively coupled to terminal c. Threshold 256 is considered to be exceeded if both (i) differentiated signal 254 exceeds 0.7 volts and (ii) control signal 244 exceeds the base voltage of Q_9 when condition (i) is met.

[118] In this way, rectified signal 240, power signal V_{t-reg} and overload detect signal 366 are used to generate error signal 239 and control signal 244. Switch 244 operates in response to differential signal 254 to selectively couple control signal 244 to the gate of linear regulator 226 (Figures 3 and 10).

[119] Figure 12 illustrates another portion of PDM control circuit 516 which uses error signal 239 to generate PDM control signal 542. PDM control circuit 516 comprises AND gates G_1 and G_2 , buffers B_1 and B_2 , resistors R_{16} , R_{17} and R_{18} , capacitors C_4 , C_5 and C_6 and diodes D_3 and D_4 .

[120] One input terminal of AND gate G_1 is coupled to terminal 712 to receive error signal 239. The other input terminal of AND gate G_1 is coupled to node 722, to receive a delay signal 724, the operation of which is explained below. When both error signal 239 and delay signal 724 exceed the high input threshold 721 of AND

gate G_1 , AND gate G_1 provides a high signal to the clock inputs CLK of buffers B_1 and B_2 .

[121] Buffer B_1 has a DATA input which is coupled to voltage source V_{cc} (which is a high signal). When AND gate G_1 provides a high signal to the clock input CLK of buffer B_1 , buffer B_1 provides a high signal at its Q output and at a node 728. At the same time, buffer B_1 will provide a low signal at its Q-not output. The Q output of buffer B_1 is coupled to ground through resistor R_{16} and capacitor C_4 . The junction of resistor R_{16} and capacitor C_4 forms a terminal 726, which is coupled to a RESET terminal of buffer B_1 . Diode D_3 is coupled in parallel with resistor R_{16} between nodes 726 and 728. Resistor R_{16} and capacitor C_4 act a delay circuit. Assuming that capacitor C_4 is initially discharged (i.e. the signal at terminal 726 is low), the high output signal at the Q output of buffer B_1 will charge capacitor C_4 . The rate at which capacitor C_4 is charged will depend on the time constant of resistor R_{16} and capacitor C_4 . Eventually the voltage at terminal 726 (and at the RESET input of buffer B_1) will become high, and buffer B_1 will reset its Q output and terminal 728 to a low signal and its Q-not output to a high signal. Capacitor C_4 will be discharged through diode D_3 and return to its initial discharged condition. Referring also to Figure 12, buffer B_1 thereby produces a pulse 732 which remains high for a time period t_9 at node 728.

[122] In an identical fashion, buffer B_2 produces a pulse 734 which remains high for a time t_{10} at terminal 730. Time t_{10} of pulse 734 will depend on the time constant of resistor R_{17} and capacitor C_5 . Diode D_5 provides a discharge path for capacitor C_5 when the Q output of buffer B_2 is low. In PDM control circuit 516, the values of resistors R_{16} and R_{17} and capacitors C_4 and C_5 are selected so that the time constant of resistor R_{17} and capacitor C_5 is shorter than the time constant of resistor R_{16} and capacitor C_4 . As a result, pulse 734 is shorter than pulse 732 (i.e. time t_{10} is shorter than time t_9).

[123] The Q-not output of buffer B_1 is coupled to ground through resistor R_{18} and capacitor C_6 . The junction of resistor R_{18} and capacitor C_6 forms node 722, which is coupled to the second input of AND gate G_1 . When the Q-not output of buffer B_1 becomes high (at the end of pulse 732), resistor R_{18} and capacitor C_6 acts a delay circuit. After a time t_{11} , capacitor C_6 will be sufficiently charged so that node 722 is a

high signal. After this time, AND gate will re-initiate the again provide a high signal to the clock inputs CLK of buffers B_1 and B_2 when error signal 239 is a high signal. This may occur immediately or may occur after some delay.

[124] The inputs of AND gate G_2 are coupled to terminals 728 and 730 to receive pulses 732 and 734. The output of AND gate G_2 is coupled to terminal 241 to provide PDM control signal 542. As described earlier, PDM control signal 542 regulates the power signal V_{s-res} produced by main power supply 518. PDM control consists of a series of pulses which have a constant on-time (during which switch 546 (Figure 10) is closed, a minimum off-time following each pulse following each pulse during which switch 546 must remain open and a variable off-time between pulses which must exceed the minimum off-time and during which switch 546 remains open.

[125] Reference is made to Figure 13. The constant on-time, minimum on-time and variable on-time of PDM control signal 542 are configured as follows. Prior to time t_a , the outputs of both buffers B_1 and B_2 are low (i.e. PDM control signal 542 is low). At this time, node 722 will have a high signal level.

[126] At time t_a , error signal 239 exceeds the high input threshold 721 of AND gate G_1 , which will then initiate the generation of pulses 732 and 734. At the same time, node 722 will fall to a low value. AND gate G_2 will begin a high pulse 740 on PDM control signal 542, since both of its inputs (at terminals 728 and 730) are high. High pulse 740 will end after time t_{10} , when pulse 734 ends. Since the time t_{10} of pulse 734 is defined only by the time constant of resistor R_{17} and capacitor C_5 , this time constant fixes the constant on-time of each high pulse of PDM control signal 542 to be equal to time t_{10} .

[127] Pulse 732 will continue until time t_9 has elapsed. During this period, node 722 has a low signal level, and therefore, the output of AND gate G_1 is low. As a result a new high pulse cannot begin on PDM control signal 542 until after time t_9 . This defines the minimum off-time of PDM control signal 542 to be equal to $t_9 - t_{10}$.

[128] When pulse 732 ends after time t_9 , the signal level of node 722 will rise and eventually will become a high signal again. After this time, a new high pulse will be initiated on PDM control signal 542 whenever error signal 239 exceeds the high

input threshold 721 of AND gate G_1 . This may occur immediately, as shown at 742 or after a delay, as shown at 744.

[129] The circuits of Figure 11 and 12 provide PDM control signal 542 and control signal 244, which control linear regulator 226 and main power supply 518 of power amplifier 600 (Figure 9). The circuit of Figure 10 may be modified to provide an error signal suitable for use in power amplifier 500 by removing the coupling between the collector of transistor Q_3 and terminal 363 (since power amplifier 500 does not include an overload detection block 362). The circuits of Figures 11 and 12 may be modified to provide a PWM control signal 242 to control the main power supply 218 of power amplifiers 200, 280, 300 or 400. A person skilled in the art will be capable of making these amendments.

[130] Reference is next made to Figure 14, which illustrates an eighth embodiment of a power amplifier 700 according to the present invention. Power amplifier 700 is a bridge amplifier which can amplify two input signals 730a and 730b simultaneously. Like power amplifier 300 (Figure 4), components of power amplifier 700 which relate only to input signal 730a are identified by a reference numeral containing the letter "a" and components of power amplifier 700 which relate only to input signal 730b are identified by a reference numeral containing the letter "b". Power amplifier 700 has two input terminals 702a and 702b, a power supply circuit 708 and two bridge amplifiers 709a and 709b.

[131] Bridge amplifier 709a includes two amplifiers 704a+ and 704a- and an inverter 705a. The input terminal of amplifier 704a+ is coupled to input terminal 702a to receive an input signal 730. The input terminal of amplifier 704a- is coupled to input terminal 702a through inverter 705a. Amplifier 704a+ amplifies positive half waves of input signal 730a. Amplifier 704a- amplifies negative half waves of input signal 730a. Together, amplifier 704a+ and 704a- provide an output signal 732a corresponding to input signal 730a. Load 734a is coupled between the outputs of amplifiers 704a+ and 704a- to receive output signal 732, which is formed between the output terminals of amplifiers 704a+ and 704a-.

[132] Similarly, bridge amplifier 709b includes two amplifiers 704b+ and 704b- and an inverter 705b, which are coupled to input terminal 702b to receive an

input signal 730b. Amplifiers 704b+ and 704b- cooperate to produce an output signal 732b between their output terminals, to which load 734b is coupled.

[133] The detailed structure and operation of bridge amplifiers 709a and 709b are set out in U.S. patent 5,075,634, entitled COMPOSITE BRIDGE AMPLIFIER, which is incorporated herein by this reference.

[134] Power supply circuit 708 is similar in structure and operation to the positive half circuits 208, 308, 408, 508 and 608. The primary difference between power supply circuit 708 and these positive half circuits is that power supply circuit 708 provides power to bridge amplifiers 709a and 709b during positive and negative half waves of input signals 730a and 730b. Accordingly there is no "negative half circuit" in power amplifier 700.

[135] Power supply circuit 708 has two input signal compensation blocks 705a and 705b, which respectively comprise offset blocks 311a and 311b, frequency compensation blocks 314a and 315b and rectifiers 715a and 715b. In order to make power supply circuit 708 operative during positive and negative half waves of input signals 730a and 730b, rectifiers 315a and 315b of power amplifier 300 have been replaced with rectifiers 715a and 715b, which are full wave rectifiers and produce full wave rectified signals 740a and 740b which are diode-or'd by diodes 360a and 360b to produce a full wave rectified signal 740 at terminal 341.

[136] Power supply circuit 708 also incorporates a number of other features of the power amplifiers described above: low voltage power supply 402, explained above in relation to power amplifier 400; overload detect blocks 362a and 362b, which respectively protect bridge amplifiers 709a and 709b and which were described above in relation to power amplifier 300; PDM control circuit 516 and main power supply 518, described above in relation to power amplifier 500; and post regulator 684, which was described above in relation to power amplifier 600.

[137] Except as described above, power supply circuit 708 operates in a matter analogous to the positive half circuits described earlier and provides a power signal V_{t-reg} at terminal 736 from which bridge amplifiers 709a and 709b receive power. Power signal V_{t-reg} is sufficient to power both bridge amplifiers 709a and 709b.

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[138] Power amplifier 700 provides the advantages of reduced headroom and reduced EMI emissions which result from the use of resonant switching regulator 516 and low voltage power supply 402. Furthermore, power amplifier 700 does not require two half circuits to provide power to its amplifiers 204a+, 204a-, 204b+ and 204b-. Power amplifier 700 provides the advantage of a predictive control system for main power supply 518 and transient power supply 223 described above in relation to power amplifier 200.

[139] Although power amplifiers 200, 280, 300, 400, 500, 600 and 700 may have reduced EMI emissions in comparison to prior art designs, a person skilled in the art will recognize that it is impossible to entirely eliminate EMI generation within such a device. Any EMI which is created within the power amplifier, and particularly within the positive and negative half circuits (or, in the case of bridge amplifier implementation, the power supply circuit) of the power amplifier may be coupled to the input terminal 202 of the amplifier. In addition, this EMI may be coupled on input signal 230 when it is received by power amplifier 200. Accordingly, it is desirable to (i) reduce the coupling of any EMI generated within the power amplifier to the input terminal and (ii) to reduce the coupling of any such EMI onto input signal 230 within the power amplifier.

[140] Reference is next made to Figure 15, which illustrates an EMI isolation circuit 800 which may be used to decouple EMI generated within the positive and negative half circuits of power amplifier 200 from the input signal 230. EMI isolation circuit 800 is explained here in the context of power amplifier 200, EMI isolation circuit 800 may also be used with power amplifiers 280, 300, 400, 500, 600 and 700.

[141] EMI isolation circuit 800 consists of a non-inverting amplification amplifier 804 and an inverting reduction amplifier 806 coupled in series between an input terminal 802 and terminal 202. (In other embodiments of EMI isolation circuit, amplifiers 804 and 806 may be non-inverting or inverting, depending on their desired operation.) Terminal 202 is the same terminal as input terminal 202 of the power amplifier discussed above, however, input signal 230 is now received at an input terminal 802, which consists of a signal input terminal 802a and a ground input

terminal 802b, and is coupled to terminal 202 through EMI isolation circuit 800.

Amplifier 804 is coupled to input terminal 802a to receive input signal 230.

[142] Positive half circuit 208, negative half circuit 210 and EMI isolation circuit 800 will typically be encased in an EMI shield 810. EMI shield 810 may be the chassis of an enclosure in which power amplifier 200 is installed. Typically, EMI shield 810 will have a ground level which may be referred to as a chassis ground 812. Positive half circuit 208 and negative half circuit 210 will have a separate power amplifier ground 814, which is floating in relation to chassis ground 812. Ground input terminal 802b and load 234 are coupled to chassis ground 812.

[143] Reference numeral 816 identifies a coupling network between chassis ground 812 and power amplifier ground 814. Coupling network 816 actually comprises all of the paths between the two separate grounds.

[144] Amplifier circuit 804 comprises an op-amp 820, resistors 822, 824 and 826 and a capacitor 828. The negative input terminal of op-amp 820 is coupled to chassis ground 812 through resistor 822 and to the output of op-amp 820 through resistor 824. The positive input terminal of op-amp 820 is coupled to signal input terminal 802a through resistor 826. Signal input terminal 802a is coupled to chassis ground 812 through capacitor 828. Resistors 822 and 826 are selected to have a large and equal resistance. Resistor 824 is selected to have a resistance much larger than that of resistor 822, thereby forming amplifier 804 into a non-inverting amplifying amplifier. Typically, resistors 822 and 826 may have a resistance of 100 k Ω and resistor 824 may have a resistance of 1 M Ω . With these values, amplifier 804 will operate as a multiply-by-10 amplifier. Preferably, amplifier 804 is configured to have an amplification of 2 to 20 times, and more preferably it will have a gain of 3 to 15 times.

[145] Amplifier circuit 806 comprises an op-amp 830 and resistors 832, 834 and 836. The negative input of op-amp 830 is coupled to the output of op-amp 820 through resistor 832 and to the output of op-amp 830 through resistor 834. The positive input terminal of op-amp 830 is coupled directly to power amplifier ground 814 and to chassis ground through resistor 836. Resistor 836 forms part of coupling

network 816. Typically, resistor 836 will have a small resistance such as 1 k Ω .

Resistor 832 is selected to have a much larger resistance than resistor 834, forming amplifier circuit 806 into an inverting reducing amplifier. Typically, resistor 832 may have a resistance of 10 k Ω and resistor 834 may have a resistance of 1 k Ω . With

these values, amplification circuit 806 will act as a divide-by-10 reducing amplifier.

[146] EMI isolation circuit 800 reduces the coupling of EMI generated within positive half circuit 208 and negative half circuit 210 onto input signal 230 within power amplifier 230 as follows. Within the context of EMI isolation circuit 800, any such EMI may be seen as an EMI signal 835 across resistor 836, which is the only coupling between the floating power amplifier ground 814 and the chassis ground 812. Input signal 230 is received across terminal 802a and 802b. Input signal 230 is amplified by amplifier 804, which provides an amplified input signal 842 across nodes 840a and 840b corresponding to input signal 230. Input signal 230 combined with EMI signal 835 form an EMI contaminated input signal 846 across terminal 844a and 844b. EMI contaminated input signal 846 is reduced by amplifier 806, providing an EMI-decoupled input 830 at terminal 202. This EMI-decoupled input signal 830 is then amplified by power amplifier 200, as described above to produce output signal 232.

[147] EMI-decoupled input signal 830 will correspond substantially to input signal 230 with a relatively small degree of contamination from EMI signal 836. This effect may be seen through the following example. If input signal 230 has a magnitude of 3 volts, EMI signal has a magnitude of -1, amplifier 804 has an amplification of 10 and amplifier 806 has an amplification of 0.1, then amplified input signal 842 will have a magnitude of 30, EMI contaminated input signal 846 will have a magnitude of 29 and EMI-decoupled input signal 830 will have a magnitude 2.9. By amplifying input signal 230 by a selected factor before it is contaminated by EMI signal 835 and then reducing EMI contaminated input signal 846 by the same factor, the effect of EMI signal 835 on input signal 230 is reduced by the selected factor, and consequently, the effect of EMI signal 835 on the operation of power amplifier 200 is reduced. It is not necessary that the amplification factor of amplifier 806 be the

reciprocal of the amplification factor of amplifier 806. The amplification factors of amplifiers 804 and 806 may be varied to provide a desired degree of reduction of EMI signal 835 and an appropriate input signal for power amplifier 200.

[148] EMI isolation circuit 800 also operates to decouple EMI signal 835 from input terminal 802, and thereby reduces the effect of EMI signal 835 on output signal 232. An EMI signal 850 corresponding to EMI signal 835 will be injected into terminals 849a and 849b at the positive and negative inputs of op-amp 820.

Resistors 822 and 826 have a high resistance, as described above, and provide a high impedance to EMI signal 850, thereby substantially decoupling EMI image signal 850 from input terminal 802. Amplifier 804, which receives input signal 230 from input terminal 802 thus receives an input signal which is not substantially contaminated by EMI.

[149] By using EMI isolation circuit 800 as an input circuit coupled to the input terminal 202 of a power amplifier according to the present invention, EMI generated within the power amplifier may be substantially decoupled both from the input terminal 202 and the input signal 230.

[150] Reference is next made to Figure 16, which is a block diagram of a ninth power amplifier 900 according to the present invention. Power amplifier 900 has an input terminal 102, an amplifier 104, and output terminal 106, a positive half circuit 908 and a negative half circuit 910, which has the same structure and a complementary operation to that of positive half circuit 908. In power amplifier 900, input compensation block 105, transient detect block 119, control circuit 116, main power supply 118 and amplifier 104 operate as in power amplifier 100. The transient operation of power amplifier 900 differs from that of power amplifier 100. Transient power supply 123 has been replaced by first and second transient control circuits 923a and 923b, which operate in conjunction with summer 937 and OR gate 902 to modify the power signal V_s produced by main power supply 118.

[151] Transient control circuit 923a has two digital output signals: a first transient control signal 904 and a second transient control signal 908. In this exemplary embodiment of power amplifier 900, transient control signal 904 is

normally low and transient control signal 908 is normally high when power amplifier 900 is in its normal operation.

[152] When transient detect block 119 detects a change in input signal 130 that requires power amplifier 900 to enter transient operation, transient control circuit 923a generates a high pulse in transient control signal 904, which is OR'd with control signal 942 to produce a main power supply control signal 906. Main power supply control signal 906 is high when either control signal 142 or first transient control signal 904 is high. Control signal 942 is a PWM signal similar to control signal 242 of power amplifier 200, and can have a duty cycle between 0 and 100%, depending on the value of compensated input signal 140. Main power supply 118 is responsive to main power supply control signal 906 and produces power signal V_s with a magnitude corresponding to main power supply control signal 906. When transient control signal 904 is low, main power supply control signal 906 is identical to control signal 142, and main power supply 118 provides power signal V_s as in power amplifier 100. When transient control signal 904 is high, main power supply control signal 906 will be high (i.e. it will have a duty cycle of 100%), and main power supply 118 will provide power signal V_s at its highest voltage.

[153] When transient detect block 119 detects a change in input signal 130 that requires power amplifier 900 to enter transient operation, transient control circuit 923a also generates a low pulse on transient control signal 908. Transient control circuit 923b receives the low pulse and increases the magnitude of error signal 939 in response to it. Control circuit 116 receives the increased error signal and increases the duty cycle of control signal 142 in response. After a selected time, transient control circuit 923a ends the high pulse on transient control signal 904 and main power supply 118 becomes responsive to control signal 142. Main power supply 118 will provide power signal V_s with a voltage level corresponding to the increased duty cycle of control signal 142.

[154] Transient control circuit 923b includes a fast attack block 910 and a slow release block 912. Fast attack block 910 operates to quickly increase the magnitude of error signal 939 in response a low pulse on transient control signal 908. Slow release block 912 operates to slowly reduce the increase in error signal 939, until,

after a selected time, transient control circuit 923b has no effect on error signal 939. Power amplifier 900 then returns to normal operation.

[155] Power amplifier 900 does not have a transient power supply (such as transient power supply 123 or 223). Instead, first and second transient control circuits 5 923a and 923b modify the power signal V_s provided by main power supply by increasing the duty cycle of main power supply control signal 906 when power amplifier 900 is in its transient operation.

[156] Reference is next made to Figure 17, which illustrates a power amplifier 1000. Power amplifier 1000 is a more detailed embodiment of a power amplifier 10 based on the general structure of power amplifier 900. Power amplifier 1000 has an input terminal 202, an amplifier 204, an output terminal 206, a positive half circuit 1008 and a negative half circuit 1010. Negative half circuit 1010 has the same structure and a complementary operation to that of positive half circuit 1008. Positive half circuit 1008 includes an input signal compensation block 205, a transient detect block 219, a control circuit 216 and a main power supply 218, which are coupled and operate in the same manner as the corresponding components in power supply 200 (Figure 2). Positive half circuit also includes first and second transient control circuits 1023a and 1023b and an OR gate 1002, which correspond to first and second transient control circuits 923a and 923b and OR gate 902 of power amplifier 900 (Figure 16).

[157] First transient control circuit 1023 includes two one-shot circuits 1030 and 1032, both of which are responsive to transient signal 257. One-shot circuit 1030 provides transient control signal 1004, which corresponds to transient control signal 904 of power amplifier 900 (Figure 16). When power amplifier 1000 in its normal operation, transient control signal 1004 is low. One-shot circuit 1032 provides transient control signal 1008, which corresponds to transient control signal 908 of power amplifier 900 (Figure 16). When power amplifier 1000 is in its normal operation, transient control signal 1008 is high. First transient control signal 1004 is OR'd with control signal 142 to generate main power supply control signal 1006, 30 which controls switch 246 of main power supply 218.

[158] When transient signal 257 becomes high, power amplifier 1000 enters its transient operation. In response to transient signal 257 becoming high, one-shot circuit 1030 provides a high pulse 1034 on transient control signal 904, causing main power supply control signal 1006 to become high. Switch 246 of main power supply 218 remains closed while transient control signal 904 is high, and main power supply 218 provides power signal V_s at its maximum voltage.

[159] Transient control circuit 1023b comprises diodes 1038, 1040, capacitors 1042, 1044 and 1046, resistors 1048 and 1050 and an amplifier 1052. The cathode of diode 1038 is coupled to the output of one-shot circuit 1032. The anode of diode 1038 defines a node 1054 and is coupled to ground through capacitor 1042. Node 1054 is coupled to the cathode of diode 1040 through parallel connected resistor 1048 and capacitor 1044. The anode of diode 1040 is coupled to a node 1056, which is also coupled to the output of amplifier 235 and to summer 237. Amplifier 1052 is coupled between the output of summer 237 and a node 1058, where it provides an amplified error signal 1039 which corresponds to error signal 239. Resistor 1050 and capacitor 1046 are coupled in parallel between nodes 1056 and 1058. Control circuit 216 is coupled to terminal 1058 and is responsive to amplified control signal 1039 to produce control signal 242.

[160] The operation of power amplifier 1000 will now be explained with reference to Figure 18. Prior to time t_{12} , power amplifier 1000 is in its normal operation. Capacitor 1042 is charged so that node 1054 has a voltage V_{1054} equal to or higher than the voltage or error signal V_{1056} at node 1056. Transient control signal 1004 is low and transient control signal 1008 is high. The normal level of transient control signal 1008 is selected to be approximately equal to or slightly higher than the maximum voltage V_{1056} (i.e. the maximum voltage across capacitor 1042 when it is fully charged). Control circuit 216 generates control signal 242 in response to amplified error signal 1039 at terminal 1058. Main power supply control signal 1006 is identical to control signal 242.

[161] Diode 1040 is optional and may be provided to prevent current from flowing from node 1054 to node 1056 when capacitor 1042 is charged. Amplifier 1000 (like amplifiers 100, 200, 280, 300, 400, 500, 600, 700 and 900) uses a closed

loop feedback through amplifier 235, summer 237 and control circuit 216 to reduce error signal 239 by keeping voltage V_{1056} approximately equal to the voltage V_{1060} of 1060 (to the extent possible, given the limits of main power supply 218). Amplifier 1052, resistor 1050 and 1046 provide an additional feedback loop, to enhance the control of error signal 239 and to keep voltages V_{1056} and V_{1060} approximately equal. Amplifier 1052, resistor 1050 and 1046 may be optionally provided in any of amplifiers described above. In normal operation, capacitor 1044 will be discharged.

[162] At time t_{12} , transient detect block 219 detects a large transient in the level of input signal 230 and sets transient signal 257 high. In response, one-shot circuit 1030 sets transient control signal 1004 high for a selected time period t_{13} and one-shot circuit 1032 sets transient control signal 1008 low for a selected time period t_{14} . Capacitor 1042 begins to discharge through diode 1038 into one-shot circuit 1032, causing voltage V_{1054} to fall. The low voltage of transient control signal 1008 is selected to sufficiently discharge capacitor 1042 that the one-shot begins to draw current from node 1056. For example, the low voltage of transient control signal 1008 may be selected to be ground, so that capacitor 1042 is fully discharged (assuming that the length of the low pulse is sufficiently long).

[163] As voltage V_{1054} falls, the feedback structure of power amplifier 1000 attempts to keep voltage V_{1056} approximately equal to voltage V_{1060} . The feedback operation and amplifier 1052 force the magnitude of error signal 239, and the amplified error signal 1039 to rise. Resistors 1048 and 1050 act as a voltage divider. Since voltage V_{1056} is controlled by the feedback structure, and since voltage V_{1054} is falling as capacitor 1042 discharges, the voltage divider helps control the voltage to which amplified error signal 1039 rises. The rate at which error signal 239 and amplified error signal 1039 rise, during an initial period t_{15} , depends on the relative resistances of resistors 1048 and 1050 and on the rate at which voltage V_{1054} falls, which in turn depends on the rate at which capacitor 1042 is discharged by one-shot circuit 1032. As amplified error signal 1039 rises, control circuit 216 increases the duty cycle of control signal 242.

[164] As capacitor 1042 is discharged, one-shot circuit 1032 begins to draw current from node 1056, and from node 1058. Capacitors 1044 and 1046 begin to

charge, allowing error signal 239 and amplified error signal 1039 to initially fall and then vary depending on the value of V_{targ} , which was described above, during time period t_{16} .

[165] During time period t_{13} , main power supply control signal 1006 is high, causing main power supply to increase the magnitude of power supply V_s through filter 250. During this time, the power signal V_t , which is identical to V_s , supplied to amplifier 204 increases, taking into account the relatively slow time constant of filter 250. Since switch 246 is held closed during this period, power signal V_t will rise relatively rapidly and amplifier 204 will receive sufficient power to produce output signal 232 in response to input signal 230.

[166] When time period t_{13} ends, transient control signal 1004 becomes low and main power supply control signal 1006 again follows control signal 242. Time period t_{13} is selected to be sufficiently long that (i) the magnitude of amplified error signal 1039 has risen, as described above in relation to time period t_{15} and the early part of time period t_{16} and (2) that the duty cycle of control signal 242 has increased sufficiently that main power supply 218 will provide sufficient power to amplifier 204 in response to control signal 242. Time period t_{13} is preferably not substantially longer than is required for these conditions to be met, since any excess power delivered to amplifier 204 will be dissipated by amplifier 204.

[167] After time period t_{14} , transient control signal 1008 becomes high again. Capacitor 1054 begins to charge until voltage V_{1054} is equal to or high than voltage V_{1056} (which will be a constantly varying voltage, depending on the magnitude of power signal V_t . If voltage V_{1056} subsequently exceeds V_{1054} , capacitor 1042 will again charge until voltage V_{1054} is equal to or higher than voltage V_{1056} .

[168] During time t_{16} , amplified error signal 1039 remains amplified by the feedback operation described above and by the voltage divider formed by resistors 1048 and 1050. At time t_{17} , power amplifier 1000 returns to normal operation and amplified error signal 1039 returns gradually to its normal value, which will depend on the difference between rectified signal 240 and compensated power signal V_{tr} .

[169] The length of time period t_{14} is selected to be long enough to allow filter 250 to charge sufficiently that power signal V_s is larger than V_{req} , and more preferably

has reached V_{targ} . This will depend on the time constant of filter 250 in any particular embodiment of a power amplifier according to the present invention.

[170] Power amplifier 1000 responds to transient signal 257 by increasing the duty cycle of main power supply control signal 1039, rather than by engaging a separate transient power supply, such as transient power supply 223 of power amplifier 200 (Figure 2). Since power amplifier 1000 has only one power supply (main power supply 218), there is no need for diode 251 (Figure 2).

[171] The structure of power amplifiers 900 and 1000 may be combined with the overload detect blocks 362 of power amplifier 300 (Figure 4) and may be used to power two or more channels, as described in relation to power amplifier 300. Power amplifiers 900 and 1000 may also be provided with low voltage power supplies 402 (and diodes 404) as described in relation to power amplifier 400 (Figure 6). Power amplifiers 900 and 1000 may also be provided with a main power supply incorporating a resonant switching regulator, such as main power supply 518 described in relation to power amplifier 500 (Figure 8), in place of main power supply 218. Power amplifier 900 and 1000 may also be provided with a post regulator 684 and the associated circuitry (rectifier 680, summer 681, amplifier 688 and summer 682), as described in relation to power amplifier 600 (Figure 10). Power amplifier 900 and 1000 may also be implemented as a bridge amplifier by modifying rectifier 215 to be a full wave rectifier as described in relation to power amplifier 700 (Figure 14). The EMI isolation circuit 800 of Figure 15 may be used to decouple EMI from the input terminal 202.

[172] A number of preferred embodiments of the present invention have been described. Many variations may be made on these embodiments, and in particular, features of some embodiments may be incorporated into other embodiments to provide an embodiment suited for a particular application. Such variations and other will be obvious to persons skilled in the art and will fall within the scope of the present invention, which is limited only by the appended claims.